# On the nature of disruptive instability in a tokamak

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The role of the interaction of plasma current with a longitudinal field in the helical instabilities is determined. It is shown that the buildup saturation of the helical modes is due only to the surface currents. A mechanism for the disruptive instability, based on the assumption that these surface currents can be effectively dissipated due to, for example, a surface helical mode which was detected elsewhere,[5] is proposed.

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The destructive instability is one of the striking and at the same time undesirable effects observed in the investigations of plasma confinement in tokamak devices. This instability causes a sudden discharge of a large fraction of plasma's thermal energy on a time scale of several tens of a microsecond, accompanied by a burst of a whole series of helical perturbations of the magnetic field, a negative voltage spike in the plasma column and an appreciable interaction of the plasma with the chamber walls. Although we now have put together a fairly comprehensive experimental picture of tearing modes,[1-3] we cannot assume that their cause is understood and that an adequate model has been developed.

Here, we shall focus attention on the equilibrium conditions of the plasma column with a current having a helical deformation of the magnetic surfaces: $\rho = a + \xi \cos(m\theta - n\zeta)$ ($a$ is the radius of a plasma column and $\theta$ and $\zeta$ are the poloidal and toroidal angles). As the calculation shows, if the plasma has a uniform current density $j_p(\rho) = \text{const}$, the function of the flux $\Psi_{\text{ext}}$ of the confining field, which must be produced by external helical windings in order to insure plasma equilibrium, has the form

$$\Psi_{ext} = -\frac{\pi}{c}\frac{\rho^m}{a^{m-2}}\cos(m\theta - n\zeta)\frac{2\xi}{a}\left[j_p\frac{m-1}{m} - j_B\right], \qquad (1)$$

  

where $j_B = (2n/mR)\,B_s$ = const is the current density at which the safety factor $q$ is equal to $m/n$. The term $j_B$ in Eq. (1) indicates that there is an interaction force in a strong, longitudinal field $B_s$ between the plasma current flowing along the helical lines and the longitudinal field. This force tends to tear the plasma column and partially performs the function of the confining field. This additional force distinguishes the helical equilibrium from the equilibrium of a linear column of noncircular cross section.

If the condition

$$j_p < \frac{m-1}{m}\, j_B\,, \quad \text{i.e.} \quad nq > m-1 \tag{2}$$

is satisfied, then the field $\Psi_{\text{ext}}$ changes its sign. This means that the mentioned tearing force associated with the longitudinal field is larger than the force constricting the plasma under the influence of the self-field. In the absence of helical windings, $\Psi_{\text{ext}} = 0$, the condition (2) indicates that a helical instability is present.

Generalizing this analysis for an arbitrary current distribution $j_b(\rho) \neq$ const, we can assume that such disruption of the helical equilibrium occurs at $nq > nq_{cr}$, where $q_{cr}$ is a value of $q$ corresponding to the left-hand boundary of the instability zone in the Shafranov diagram.[4,5] It is well known that if the condition $nq > m$ is satisfied, then the ideal mode can be stabilized, but, as one can easily establish, only due to the surface currents produced as a result of plasma-column deformation. Since the cause of the instability associated with the bulk plasma current cannot be eliminated, an allowance for dissipation must lead to an instability which indeed was detected by Zakharov[5] and is, by definition, a surface helical mode.

On the basis of the above discussion, we propose the following picture of the disruptive instability. 1) During the stable phase the discharge in the tokamak corresponds to the helical mode located on the left-hand side of the instability zone.[5] It is reasonable to assume that here we must choose the diagram for the mode $m = 2$, $n = 1$, irrespective of the value of $q$ in the diagram. 2) A disruptive instability can be produced by decreasing the current at the center of the plasma column, which can be linked, for example, to an internal disruption. The discharge on the left-hand side in this case enters the zone of the helical-instability mode $m = 2$, $n = 1$. If the current density decreases to the extent that $q(0)$ at the center of the column is larger than unity [condition (2)], then this will lead to a turning of the plasma column inside out, so that its central part will come out to the surface and the cold, peripheral plasma will be at the center. This indicates a large disruption. If the decrease of the current density is not appreciable, then only the periphery of the plasma column will be rearranged, which corresponds to a small disruption. 3) Assuming that after the plasma has been inverted its core will spread along the surface of radius $d$; we can easily obtain from the condition of magnetic-flux conservation, which has the following form for a helical flow

$$\int_0^b \left(B_\theta(\rho) - \frac{n\rho}{mR} B_s\right) d\rho = \int_d^b \left(B_\theta^1(\rho) - \frac{n\rho}{mR} B_s\right) d\rho \tag{3}$$

$[B_\theta(\rho), B^1_\theta(\rho)$ is the current field before and after the instability and $b$ is the radius of the effective shell], the following equation for the variation of the plasma current:

$$\frac{\delta I}{I} = \frac{2\, l_i^\psi - \frac{n}{m}\, q\,(d)}{\ln \frac{b^2}{d^2}}\ , \quad l_i^\psi = \frac{c}{2I}\int_0^d B_\theta\,(\rho\,)\,d\,\rho\,. \tag{4}$$

If $d$ is smaller than the so-called mixing radius,[6] then $\delta I > 0$, which gives a negative peak for the bypass voltage. 4) According to the ideas developed by Kadomtsev,[6] after a specific helical mode is completed the value of $q(0)$ is equal to $m/n$ at the center of the plasma column. According to Eq. (2), this means that the conditions for the next mode $m+1$, $n$ have been satisfied. Therefore, a series of modes $m = 3{,}4$, etc. occurs after the completion of the mode $m = 2$.

Note that the widespread viewpoint that the helical instability is stabilized at the nonlinear stage due to shear is incorrect. The cause of the instability identified above apparently cannot be eliminated as a result of development of this mode. The stabilization observed in the numerical calculations,[7] however, is totally attributable to the surface current that appears in the ideal-conductivity model. For a helical deformation of the plasma column, we can see from the condition of conservation of the value $\mu = 1/q$ that

$$2\mu = 1 + \left(\frac{I_p}{S j_B} - 1\right)\frac{2\lambda}{\lambda^2 + 1}\ . \tag{5}$$

We can see from the cross-sectional area $S$ that the bulk plasma current $I_p$ increases ($\lambda$ is the ratio of the cross-sectional semiaxes), and this excites the reverse surface current, which, as can easily be seen, plays the stabilizing role. On the basis of the results obtained by Zakharov,[5] we can assume that the surface current is effectively dissipated due to the surface helical mode. Therefore, there is no nonlinear stabilization for the finite-conductivity plasma.

The most comprehensively developed disruptive-instability model,[8] which is based on the interaction between the tearing modes $m = 2$, $n = 1$ and $m = 3$, $n = 2$ is not convincing. As Zakharov's investigation shows,[5] the plasma beneath the resonance surface is unstable and hence cannot have a high conductivity and appreciable current. A model with a free boundary corresponds more closely to these tokamak conditions. However, the harmonic $m = 3$, $n = 2$ observed in the experiments can be attributed to the fact that the condition (2) for its occurrence: $q(0) > 1$ corresponds to that for the occurrence of the mode $m = 2$, $n = 1$, i.e., the fractional harmonic is not dominant, although it can develop.

In conclusion, we should mention that since it is probably impossible to prevent a discharge of current density at the center of the plasma column, although this would be a radical way to avert a disruption, we should consider the possibility of stabilizing the mode $m = 2$, $n = 1$ by means of the shell which in this case is the tokamak's liner. The smaller the difference in size of the current channel and the shell, the stronger is its effect. This means that the low-$q$ modes at the plasma boundary are the most promising.

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[1]S. V. Mirnov and N. B. Semenov, Preprint Kurchatov IAE, No. 2723, 1976.
[2]V. G. Merezhkin, Preprint Kurchatov IAE, No. 2790, 1977.
[3]DIVA Group, Nucl. Fusion **20**, 271 (1980).
[4]V. D. Shafranov, Zh. Tekh. Fiz. **40**, 241 (1970) [Sov. J. Tech. Fiz. **15**, 175 (1970)].
[5]L. E. Zakharov Pis'ma Zh. Eksp. Teor. Fiz. **31**, 300 (1980) [JETP Lett. **31**, (1980) (in press)].
[6]V. V. Kadomtsev, Plasma Phys. and Contr. Nucl. Fusion Res. Vol. 1, IAEA, Vienna, p. 555, 1977.
[7]R. White, D. Monticello, M. Rosenbluth, H. Strauss, and V. V. Kadomtsev, Plasma Phys. and Contr. Nucl. Fusion Res., Vol. 1, IAEA, p. 495, 1975.
[8]B. V. Waddell, B. Carreras, H. R. Hicks, and J. A. Holmes, Phys. Fluids **22**, 896 (1979).